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The effect of methane hydrate morphology and water saturation on seismic wave attenuation in sand under shallow sub-seafloor conditions

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ABSTRACT

A better understanding of seismic wave attenuation in hydrate-bearing sediments is needed for the improved geophysical quantification of seafloor methane hydrates, important for climate change, geohazard and economic resource assessment. Hence, we conducted a series of small strain ($<10^{-6}$), seismic frequency (50–550 Hz), laboratory resonant column experiments on synthetic methane hydrate-bearing sands under excess-water seafloor conditions. The results show a complex dependence of P- and S-wave attenuation on hydrate saturation and morphology. P- and S-wave attenuation in excess-water hydrate-bearing sand is much higher than in excess-gas hydrate-bearing sand and increases with hydrate saturation between 0 and 0.44 (the experimental range). Theoretical modelling suggests that load-bearing hydrate is an important cause of heightened attenuation for both P- and S-waves in gas and water saturated sands, while pore-filling hydrate also contributes significantly to P-wave attenuation in water saturated sands. A squirt flow attenuation mechanism, related to microporous hydrate and low aspect ratio pores at the interface between sand grains and hydrate, is thought to be responsible for the heightened levels of attenuation in hydrate-bearing sands at low hydrate saturations (<0.44).

1. Introduction

Detection and quantification of seabed methane is important for predicting greenhouse gas fluxes between the seabed, the water column and the atmosphere and their impact on future climate change. The highest concentrations of seabed methane are thought to occur in association with seabed methane hydrates that are especially sensitive to global warming in polar regions. Methane hydrates are ice-like compounds of methane and water that are stable at water depths greater than about 300 m for typical seafloor temperatures of 4 °C; perturbations in bottom water temperature can cause hydrates to dissociate and release methane gas into the water column (Westbrook et al., 2009). Methane gas and methane hydrate quantification techniques are also needed for assessing seafloor geohazards (e.g., landslides associated with hydrate dissociation on continental slopes) and hydrate energy resources (hydrate reservoir characterisation) (Riedel et al., 2010).

Seismic geophysical methods can be used to image and quantify gas hydrates and free gas in sediments (Ecker et al., 1998, 2000; Guerin and Goldberg, 2002; Matsushima, 2006; Pratt et al., 2005; Riedel et al., 2010; Westbrook et al., 2008; Wood et al., 2000) given suitable knowledge of how seismic velocity and attenuation relate to hydrate content and morphology, and sediment type (Chand et al., 2006; Lee, 2002; Waite et al., 2010; Yun et al., 2005). However, the interpretation of in situ seismic attenuation measurements is uncertain because of our limited understanding of attenuation mechanisms in sediments in general, and the role of hydrate in particular. It is often difficult to unambiguously relate attenuation measurements from seismic surveys and sonic well logs to specific hydrate or sediment conditions because of spatial averaging effects, so laboratory studies are more suitable in this respect. However, given a uniform sediment sample, isolating intrinsic loss mechanisms and accurately predicting their dependence on, for example, measurement frequency, effective pressure, temperature, pore fluid type and saturation, hydrate saturation and morphology, are major challenges.

In this paper, we present novel, laboratory resonant column results for seismic compressional and shear wave attenuation measured in water saturated, synthetic methane hydrate-bearing sand created under excess-water conditions at an effective pressure of 500 kPa and a temperature of 10 °C, representative of shallow sub-seabed hydrates. The results show that attenuation is significantly higher than that observed by Priest et al. (2006) in methane gas saturated, methane hydrate-bearing sand

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where the hydrate was created under excess-gas conditions using the same apparatus. In an attempt to study the possible contribution of different hydrate morphologies to intrinsic attenuation, we introduce the Hydrate Effective Grain (HEG) model based on the notion of microporous hydrate grains. Comparison with the resonant column observations suggests that the amount of load-bearing hydrate in particular is an important control on P- and S-wave attenuation, while pore-filling hydrate also affects P-wave attenuation in water saturated sands.

2. Experiments

2.1. Gas hydrates resonant column

We performed a series of laboratory experiments on Leighton Buzzard sand specimens (7 cm diameter, 14 cm high solid cylinders) using the gas hydrates resonant column (GHRC) developed in Southampton, United Kingdom. Previous studies focused on methane saturated, synthetic methane hydrate-bearing sand prepared using the excess gas method (Best et al., 2010; Clayton et al., 2005; Priest, 2004; Priest et al., 2005, 2006). Here, we present new data for water saturated, synthetic methane hydrate-bearing sand prepared using the excess water method as described in Clayton et al. (2010), Priest et al. (2009) and Rees (2009).

The main advantage of the resonant column method for elastic wave propagation studies is that it enables all four seismic parameters of interest (V_p, V_s, Q_p^{-1}, Q_s^{-1}) to be measured at similar frequencies (50–550 Hz) to those used during in situ seismic surveys. Here, V_p and V_s are the body wave P- and S-wave velocities, respectively, and Q_p^{-1} and Q_s^{-1} are the P- and S-wave attenuations (inverse quality factors Q_p, Q_s), respectively. All measurements were conducted in a temperature-controlled cell under a simulated hydrostatic effective stress of 500 kPa with a pore fluid pressure of 15 MPa and a temperature of 10 °C. The specimens were excited in torsional and longitudinal flexural resonance by sweeping the drive frequency around the specimen fundamental mode frequencies and monitoring the resultant vibration amplitude via an accelerometer attached to the drive mechanism mounted on the top of the specimen.

The torsional and longitudinal flexural specimen velocities were calculated from the observed resonant frequencies along with knowledge of the specimen size and mass, and mass polar moment of inertia of the top cap. Shear and Young's moduli can be derived from the velocities and the calculated specimen density. The P-wave modulus and bulk modulus were then derived using well-known relationships (Birch, 1961). Attenuation was measured for both excitation modes from the free vibration amplitude decay curve after the power to the drive system was turned off (Priest et al., 2006). Attenuation was first measured as the logarithmic decrement, then converted into quality factor Q and the specific dissipation function Q^{-1}. Knowledge of the torsional (shear modulus) and longitudinal flexural (Young's modulus) attenuations allowed derivation of the P-wave and bulk modulus attenuations using relationship given by Eqs. (1)–(3) in Winkler and Nur (1979).

A particular feature of the resonant column configuration is that, using the torsional and longitudinal flexural modes, it is only possible to measure the frame elastic moduli of a porous medium with significant permeability like sand specimens. That is, even in the case of a water saturated specimen, only the velocities and elastic moduli associated with the solid framework of mineral grains are measured. Both vibration modes involve no volume change in the bulk specimen, so it is impossible to measure directly the compressional wave properties of the bulk system of fluid and framework of solid mineral grains. Although this adds complexity to the interpretation, the results are still useful as will be shown below. Although the measured resonant column attenuations are partly caused by global viscous fluid flow between the fluid and frame, the direction of fluid flow is particular to the resonance modes. While this is equivalent for torsional vibration in the resonant column and for shear (S) body waves in the Earth, the same cannot be said for longitudinal flexural vibration in the resonant column and for compressional (P) body waves. For the flexural mode, the fluid flow is perpendicular to the wave propagation direction (see Fig. 1), while it is parallel with the wave propagation direction for P-waves. However, we take these attenuations to be equivalent if we assume the sand specimens are homogeneous and isotropic. What is important is the observed magnitude of attenuation due to average fluid flow in the bulk sand specimens under frame shear and longitudinal flexural vibration. Also, any local viscous fluid flow mechanism will be relatively unaffected by the macroscopic (global) fluid flow.

2.2. Methane hydrate formation, morphology and seismic velocity

Methane hydrate was formed in the sand specimens using two methods: excess gas (Priest et al., 2005) and excess water (Priest et al., 2009). The excess gas method involves distributing a known mass of water throughout the sand specimen, saturating the partially water saturated sand with methane gas, then taking the specimen into the hydrate stability field. The velocity and elastic moduli results indicated a grain cementing hydrate morphology that led to a rapid increase in velocity with hydrate saturation up to about 5%, as reported in Clayton et al. (2005) and Priest et al. (2005). Water tends to coat the water–wet sand grains and so the methane reacts with the water to form grain-coating hydrate, a proportion of which acts to cement the grains at grain contacts (Chand et al., 2006). By contrast, the excess water method involves injecting methane gas into the specimen and then flooding the sand specimen with water before taking the specimen into the hydrate stability field. This is thought to produce a pore-filling hydrate morphology as the methane gas

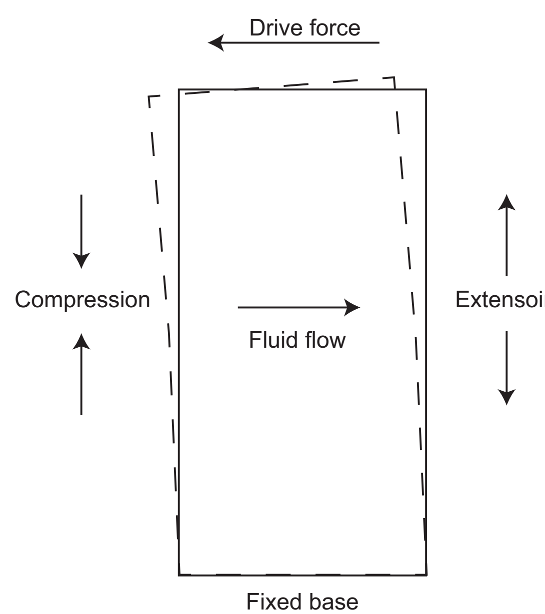

Fig. 1. Diagram showing the direction of fluid flow in a porous sand specimen during longitudinal flexural excitation inside the resonant column. The solid framework of mineral grains undergoes compression and extension while the saturating fluid flows horizontally from the side under compression to the side under extension.